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INVESTIGATION OF THE PYROMETALLURGICAL, PHYSICAL AND MECHANICAL BEHAVIOR OF WELD METAL

Final Report

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The physical and chemical behavior of welding consumables were investigated. The influence of strain and weld metal composition on weld metal microstructure, properties and cracking behavior were studied. Advanced concepts were evaluated to produce higher purity and more consistent welding consumables. New methods to quantify welding consumables were studied.

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Scope

The physical and chemical behavior of welding consumables were investigated. The influence of strain and weld metal composition on weld metal microstructure, properties and cracking behavior were studied. Advanced concepts were evaluated to produce higher purity and more consistent welding consumables. New methods to quantify welding consumables were studied.

1.0 STATEMENT OF THE PROBLEM

Four different research topical areas are addressed, but all are concerned with the pyrometallurgy and physical metallurgy of weld metal. These topical research areas are entitled the following:

a. Steel weld metal phase transformation

b. Weld metal pore formation and methods to retard porosity

c. Advances in welding flux research

d. The hot cracking behavior of aluminum alloys.

1.1 Steel Weld Metal Transformations

The mechanisms of nucleation and growth of weld metal acicular ferrite are being determined at the Colorado School of Mines. The size and amount of acicular ferrite is known to be a major consideration to achieve optimum strength and toughness in low carbon steel weld metal. The present research was to determine the influence of macro and micro strain energy on the nucleation and growth of acicular ferrite. A model is needed to quantitatively predict the amount and nature of strain to cause a measurable influence on weld metal microstructure. An effort to investigate the role of weld metal boron with titanium in promoting acicular ferrite was undertaken. This topic is important since titanium-boron welding consumables are being accepted as a primary method to achieve optimum mechanical properties (both strength and toughness) in low carbon steel weld metal. A fundamental understanding of the specific role of these elements is necessary if new advanced welding consumables are to be developed and optimized based on sound metallurgical concepts.

1.2 Weld Metal Pore Formation and Methods to Retard Porosity

Weld metal porosity is becoming a more visible defect with the advances in non destructive testing. It is also a concern since design engineers are requiring higher mechanical integrity for welded assemblies. A fundamental knowledge of weld metal pore formation is needed to find new methods to reduce weld metal porosity. A parallel effort is needed to obtain a "fitness-for-purpose" criteria for pores since a specific pore density may not degrade the weld metal integrity. The mechanical behavior of weld metal with known levels of porosity under conditions of tensile and cyclic loading, impact, etc. needs to be carefully characterized and modeled. This investigation needs to establish a fundamental understanding of the nucleation and growth of weld metal pores. Theoretical models are required which can predict the formation of hydrogen porosity based on an alloy composition, welding process variables, and welding conditions.

1.3 Advanced Flux Systems

The Colorado School of Mines has had an extensive ARO welding flux research program investigating physical and chemical behavior of the SiO_2-CaO-CaF_2, SiO_2-TiO_2-CaO and SiO_2-MnO-X welding flux systems where X represents over 16 different oxide and flouride additions. Over 250 different flux compositions have been characterized and their behavior modeled to investigate the pyrometallurgical behavior of flux and its influence on low carbon steel weld metal composition and microstructure. Phase transformations in low carbon steel weld metal made by the submerged arc welding processes using these fluxes are being studied. A model is

needed for the roles of oxygen, inclusion type, and size distribution on phase transformations. New methods to make higher purity and more compositionally consistent welding fluxes need to be investigated and developed.

1.4 Aluminum Weld Metal Cracking Mechanism

A research effort to determine the fundamental nature of hot cracking in aluminum weld metal has been in progress at the Colorado School of Mines. This effort has evaluated the cracking susceptibility of Al-Li alloys. Selected binary aluminum alloys were investigated to relate their eutectic temperatures to the thermal history experienced at the position of the crack tip and a model was developed and tested. An investigation was made into the effectiveness of microadditions of grain refiners to aluminum-lithium weld metal. A mechanistic model is needed for the effectiveness of these grain refiners in altering the solidification structure and cracking susceptibility in aluminum alloy welds.

2.0 SUMMARY OF RESULTS

2.1 Steel Weld Metal Phase Transformations

Weld metal toughness is strongly influenced by the volume fraction of acicular ferrite which forms as a product of austenite decomposition. The extent of acicular ferrite formation is influenced by macro strain energy (involving the mechanical state of the whole weld bead) or the strained austenite adjacent to non-metallic inclusions has been a mechanistic question in understanding the development of low carbon steel weld metal microstructure. Research efforts in this investigation showed a small influence of tensile or compressive stress on acicular ferrite formation, but a larger influence from the austenite grain size (see publication #14). The results suggest that thermal expansion mismatch between the non-metallic inclusion and the surrounding austenite is not a primary factor in the production of acicular ferrite. A further characterization of the role of non-metallic inclusions on the formation of weld metal microstructure was performed (see publications #1 and #8). These results indicate that with proper selected welding consumable compositions, the optimum inclusion type, amount and size distribution can be obtained which can produce advancement in weld metal mechanical properties. The next effort should be to develop analytical methods to predict the proper selection of consumable compositions to achieve equal properties for various changes in thermal experiences (heat inputs). The results of this investigation is the first step toward this end.

The resulting mechanistic understanding of the role of weld metal oxygen (non-metallic inclusions) on submerged arc weld metal microstructure was translated to the gas metal arc weld metal metallurgy

(see publications 4 and 10). It was demonstrated that concepts used to understand SAW metallurgy also can be used to predict GMA weld metal microstructure

The influence of boron and titanium additions on acicular ferrite formation was investigated. The results of these experiments showed a maximum in ductility with respect to both boron and titanium contents. Titanium and boron contents below the optimum produced too little hardenability and to few Ti-rich inclusions to form a substantial volume fraction of acicular ferrite. Titanium and boron contents above the optimum produced a bainitic microstructure with reduced ductility. The low carbon steel weld metal mechanical properties were determined as a function of weld metal titanium and boron contents (see publication #11). These results characterized the compositional (Ti and B) region for optimum properties and offer the optimum composition to promote further modifications to increase weld metal strength through precipitation strengthening.

2.2 Weld Metal Pore Formation

A comprehensive review of the nucleation and growth of weld metal pores was completed (see publication #24). This review included the influence of welding parameters on pore formation and methods to retard weld pool porosity.

2.3 Advanced Flux Systems

Research programs concerned with welding fluxes were carried out to evaluate the pyrometallurgical behavior of oxide/flouride fluxes, and

determine their influence on low carbon steel weld metal composition and microstructure, (see publications #2,4,13,15 and 16). The influence of electrochemical reactions in DC arc welding processes on weld metal composition was investigated (see publications #3,6, and 9).

An investigation using both straight and reversed polarity submerged arc welds have shown that both electrochemical and thermochemical reactions play important roles in controlling weld metal composition. Electrochemical reactions dominate at the tip of the electrode and at the weld pool surface, and thermochemical reactions promote composition changes which move toward thermochemical equilibrium in the detached droplet and in the weld pool after passage of the arc. The electrochemical reactions include: oxidation of alloy and tramp elements at the anode, and reduction of tramp and alloy elements at the cathode.

These electrochemical experiments have demonstrated that weld metal composition can be better controlled for a specific consumable combination by selection of the optimum welding parameters (current, voltage, travel speed and electrode polarity). It may offer methods to reduce weld metal hydrogen pick up during welding with the use of proper welding parameters.

The SiO_2-CaO-TiO_2-1%Na_2O fluxes were made by the sol gel process which has been used to make homogeneous high purity ceramic chemicals. The sol gel process has also been demonstrated to achieve properties of the welding process which will be necessary for fluxes that are to be used for advanced automatic welding processes with microprocessor-feed back controls (see publication #5).

With wet underwater welding consumable research (which increases one bar of pressure for each 33 feet increase in water depth), it was possible

to identify the role of specific welding pyrochemical reactions and to demonstrate that metallurgical fundamentals can be used to develop new consumables which can achieve properties in stringent environments (see publications #25,26, and 27).

A compacitance method has been developed to nondestructively measure the moisute content in the flux of the coating of a covered electrode. The technique could be used as a quality assurance test for welding consumables or as a quick field test to determine when covered electrodes need to be rebaked. This development can be extremely cost effective in reducing cold cracking associated with high strenght steel weldments (see publication #12).

2.4 Aluminum Weld Metal Cracking

Research concerned with cracking in aluminum alloy welds have been carried out using varestraint and transvarestraint tests on Al-Li and commercial aluminum alloys to determine the variables contributing to weld metal cracking (see publicationss #17,18,19,20, and 21). The influence of grain refiners on weld metal microstructure and hot cracking susceptibility was also investigated (see publications 22 and 23).

The experimental results showed that Al-Li-Cu alloys without sufficient grain refiners have a high susceptibility of hot tearing and inferior weldability. Additions of titanium and zirconium in the range of .05 to .30 wt pct were shown to improve the weldability by providing $TiAl_3$ or $ZrAl_3$ particles which act as heterogeneous nuclea·ion sites for refinement of the weld solidification structure.

Weldability showed a continuous improvement over the range of Ti and Zr concentrations that were examined. Therefore, it is expected that optimum weldability will be achieved at grain refiner concentrations in excess of 0.30 wt pct.

3.0 RESEARCH PUBLICATIONS RESULTING FROM ARO SUPPORT (1986-1989)

3.1 Ferrous Welding Consumables and Weld Pool Metallurgy

1. S. Liu and D.L. Olson, "The Role of Inclusions in Controlling HSLA Steel Weld Metal Microstructures", Welding Journal 65(6), 139s-149s (1986).

2. C.A. Natalie, D.L. Olson and M. Blander, "Behavior of Welding Fluxes", Annual Review of Materials Science 16, 389-413 (1986).

3. M. Blander and D.L. Olson, "Electrochemical Effects on Weld Pool Chemistry in Submerged Arc and D.C. Electroslag Welding", Proc. Int. Conf. on Trends in Welding Research, Gatlinburg, TN, May 19-22 (1986), pp. 363-366, ASM, Metals Park, Ohio (1986).

4. O. Grong, T.A. Siewert, G.P. Martins and D.L. Olson, "A Model for the Silicon-Manganese Deoxidation of Steel Weld Metals", Met. Trans. 17A (10), 1797-1807 (1986).

5. P.S. Dunn, C.A. Natalie and D.L. Olson, "Sol Gel Fluxes for Flux Cored Welding Consumables", J. Mat. for Energy Systems 8 (2), 176-184 (1986).

6. J.H. Kim, R.H. Frost, D.L. Olson and M. Blander, "Electrochemical Reactions at the Electrode in Submerged Arc Welding", Proc. of Joint International Symposium on Molten Salts, Honolulu, Hawaii, Electrochemical Society, Pennington, N.J. (October 18-23, 1987).

7. J.L. McCall, D.L. Olson, and I. LeMay, (editors), "Metallography and Interpretation of Weld Microstructures", Symposium Proceedings, pp. 1-393, ASM International, Metals Park, Ohio (1987).

8. S. Liu and D.L. Olson, "The Influence of Inclusion Chemical Composition on Weld Metal Microstructure", J. Mat. Eng. 9, 237-251 (1987).

9. J.H. Kim, R.H. Frost, D.L. Olson, and M. Blander, "Effect of Electrochemical Reactions on Submerged Arc Weld Metal Composition", submitted to Welding Journal (1988).

10. R.E. Francis, J.E. Jones and D.L. Olson, "Effect of Shield Gas Oxygen Activity on GMA Microalloyed HSLA Steel Weld Metal Microstructure", submitted to Welding Journal (1988).

11. D.W. Oh, D.L. Olson and R.H. Frost, "The Influence of Boron and Titanium on Low Carbon Microalloyed Steel Weld Metals", submitted to the Welding Journal (1988).

12. D.E. Bunnell D.L. Olson, and S. Liu, "Moisture Determination of SMAW Electrode Coverings Using Electrical Capacitance", accepted for publication in J. Eng. Mat. (1989).

13. C.A. Natalie, D.L. Olson, and M. Blander, "Weld Pool Pyrometallurgy", Materials Processing - Theoretical Practice 8 (Welding Theory and Practice), Chap. 5, pp. 149-174, North Nolland Physics, Elsevier Science Publisher, NY, NY (1989).

14. C.B. Dallam and D.L. Olson, "Stress and Grain Size on Weld Metal Ferrite Formation", Welding Journal 68 (5), 198s-205s (1988).

15. P.A. Burke, J. E. Indacochea, and D.L. Olson, "The Influence of Submerged Arc Welding Flux on AISI 4340 Steel Weld Metal Composition and Microstructure", to be submitted to Welding Journal (1989).

16. D.L. Olson, "The Fundamentals of Welding Consumables", Proc. Gatlinburg Conference, pp ____, ASM, Metals Park, Ohio, May (1989).

3.2 Non-Ferrous Welding Consumables and Weld Pool Metallurgy

17. C.E. Cross and D.L. Olson, "Weld Metal Solidification and Hot Tearing of Aluminum Alloys", Solidification Seminar, Centennial Technical Symposia, ALCOA Laboratories, p. 46, August 24-28 (1986).

18. C.E. Cross and D.L. Olson, "Hot Tearing Model to Assess Aluminum Weldability", Proc. Int. Conf. on Aluminum Alloys: Physical and Mechanical Properties, Univ. of Virginia, Charlotteville, VA, July 15-20, (1986), vol. III, pp. 1869-1875 (1986).

19. C.E. Cross and D.L. Olson, "Characterization of Binary Aluminum Alloy Weld Metal Microstructures", Microstructural Science 14, "Welding Failure Analysis and Metallography", pp. 3-16, ASM, Metals Park, OH (1987).

20. C.E. Cross, G.R. Edwards, D.L. Olson and R.H. Frost, "Intrinsic Nucleation of Weld Metal Grains", Conf. Proceedings on Solidification Processes, pp. 388-391, Sheffield, U.K., September (1987), The Institute of Metals, London (1988).

21. C.E. Cross and D.L. Olson, "Compositional Factors Affecting Weldability of Extruded Aluminum Alloys", Conf. Proc. 4th Int. Alum. Extrusion Tech. Seminar, 2, pp. 391-393, Chicago April 11-14 (1988).

22. M.J. Dvornak, R.H. Frost, and D.L. Olson, "The Weldability and Grain Refinement of Al-2.2 Li-2.7 Cu Alloy", submitted to Welding Journal (1988).

23. He Yunija, R.H. Frost, G.R. Edwards and D.L. Olson, "Influence of Grain Refinement on the Weldability of Aluminum Alloys", to be published in the Welding Journal (1987).

24. R. Trevisan, D.D. Schwemmer, and D.L. Olson, "The Fundamentals of Weld Metal Pore Formation", Materials Processing - Theory and Practice 8 (Welding Theory and Practice), Chap. 3, pp. 79-116, North Holland Physics, Elsevier Science Publishers, NY, NY (1989).

3.3 Special Welding Consumable Research and Patents

25. D.L. Olson and S. Ibarra, "Underwater Welding Metallurgy, Proceedings ASME, "First OMAE Specialty Symposium on Offshore and Arctic Frontiers", ASME, New York, N.Y., pp 439-447, (1986).

26. S. Ibarra, C.E. Grubbs, and D.L. Olson, "The Nature of Metallurgical Reactions in Underwater Welding", 1987 Offshore Technology Conference, OTC Report 5388 pp. 277-282, (April 27, 1987).

27. S. Ibarra, C.E. Grubbs, and D.L. Olson, "Metallurgical Aspects of Underwater Welding", J. of Metals 40 (12), 8-10 (1988).

28. D.L. Olson and A.M. Davila, "Cast Iron Welding Materials", European Patent EP0038820 and West Germany Patent P3071827.5, November 12 (1986).

29. D.L. Olson and A. Davila Marquez, "Cast Iron Welding Electrodes", U.S. Patent Number 4,726,854 February 23 (1988).

4.0 PARTICIPATING SCIENTIFIC PERSONNEL

R.H. Frost - Co-Principal Investigator

D.L. Olson - Co-Principal Investigator

C.E. Cross - Graduate Research Assistant (completed PhD, 1986)

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K.P. Marts - Graduate Research Assistant (completed MS, 1987)

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